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FRUITS of the sea? A cautionary tale regarding Bayesian modelling of palaeodiets using stable isotope data

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Abstract

A recent paper by Bownes et al. (2017, *Radiocarbon* 59(5): 1275-1294) used the Bayesian modelling software package FRUITS (Fernandes et al. 2014, *PLoS ONE* 9(2): e87436) to argue that Neolithic individuals from Carding Mill Bay on the west coast of Scotland obtained up to ca. 21% dietary protein from marine sources. This is in contrast to previous interpretations of the same isotopic ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) data, which concluded that these individuals showed little if any use of marine resources (Schulting and Richards 2002, *European Journal of Archaeology* 5(2): 147-189). Resolving this discrepancy is important for our understanding of the nature of the Mesolithic–Neolithic transition not only on the west coast of Scotland, but along all of Atlantic Europe, since similar isotopic results to those obtained at Carding Mill Bay are widespread throughout the Neolithic and indeed later periods. We suggest that greater caution needs to be exercised in the interpretation of the output of Bayesian palaeodietary modelling, which can be very useful heuristically, but should not always be taken at face value. Given the large number of parameters employed in such models (diet isotopic values and nutrient concentrations, trophic level and tissue fractionations, etc.) and the uncertainty involved in almost all of them, a wide range of outcomes are possible, as we demonstrate in this paper. We reaffirm the overwhelmingly terrestrial nature of diet at Carding Mill Bay both through FRUITS modelling and through the new application of compound-specific $\delta^{13}\text{C}$ analysis of single amino acids of humans and fauna from the site.

Keywords: Stable carbon and nitrogen isotopes; Compound-specific isotope analysis; Neolithic Scotland; Carding Mill Bay; Bayesian modelling of palaeodiets; Marine versus terrestrial diets

Introduction

There has been a long-running debate over the degree of continued utilisation of marine resources between the Mesolithic and the Neolithic of coastal northwest Europe, one that comes into particularly sharp focus in Britain. It is little exaggeration to say that the debate has been polarised, with some researchers arguing for a strong element of ‘continuity’ between Mesolithic and Neolithic subsistence practices (Armit and Finlayson 1992; 1996; Thomas 2003; 2004; 2007; 2013), and others – the present authors included – arguing for a ‘sudden, sharp shift’ in diet between the two periods, from an emphasis on hunting, fishing, and gathering wild resources in the Mesolithic, to an emphasis on domesticated plants and animals in the Neolithic (Cramp et al. 2014; Richards et al. 2003; Richards and Schulting 2006; Rowley-Conwy 2004; Rowley-Conwy et al. 2020; Schulting 2013; Schulting and Richards 2002a; 2002b; Sheridan and Schulting 2020; Smyth and Evershed 2015)¹. Others have taken an intermediate position, accepting that there was a marked change in diets, but that this was slower and less extreme than has been claimed (Charlton et al. 2016; Cummings and Harris 2011; Lidén et al. 2004; Milner et al. 2004). Given the ambiguities in interpreting archaeobotanical and zooarchaeological assemblages, stable carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) isotope analysis of human remains has played a very large – and, we would add, deciding – role in this debate (Richards and Schulting 2006). Given the strength of isotopic data as direct evidence for the foods (at least in terms of terrestrial versus marine resources) consumed over many decades by individuals, some of the questions raised relate to the interpretation of stable isotopic results, and whether they have served to exaggerate our impression of the dietary shift between Mesolithic and Neolithic coastal communities in Britain, and, by implication, elsewhere in Europe (Milner et al. 2004; see reply in Richards and Schulting 2006). This is the approach taken in the paper by Bownes et al. (2017), which uses Bayesian modelling of previously published human isotopic data on individuals directly dated to the mid- to late-fourth millennium BC from the site of Carding Mill Bay, near Oban on the west coast of Scotland. Revisiting this issue is important, since it not only impacts on our understanding of the Mesolithic-Neolithic transition and that of Neolithic diets in the subsequent centuries, but also because it affects our basic interpretation of stable isotopic data more widely, and this is a crucial issue in any context.

¹ This position is also more consistent with the recent genetic evidence for a large-scale population replacement in Britain (Brace et al. 2019).

Bownes et al. (2017: 1276) refer to our interpretation of the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ evidence as indicating a lack of significant marine resources in the Neolithic individuals at Carding Mill Bay (Schulting and Richards 2002a) as being at odds with the archaeological evidence, given that the site is a shell midden. While we did emphasise the ‘sharp shift’ in diets seen with the appearance of the Neolithic, this needs to be seen in the context of debates at the time, which were emphasising a strong degree of continuity in the subsistence economy across the Mesolithic-Neolithic transition (e.g., Armit and Finlayson 1992; 1996; Finlayson and Edwards 1997; Mithen and Finlayson 1991; Richmond 1999; Thomas 1996; 2003; Whittle 1996). Even so, the possibility of a small contribution of marine foods was acknowledged: “The remarkably tight clustering of all human samples from Carding Mill Bay (CMB) and Crarae strongly implies an isotopically homogeneous diet *with minimal input of marine foods*” (Schulting and Richards 2002a: 157, emphasis added). This statement was and remains fully justified in light of the clear separation of both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ results from Mesolithic Oronsay (Richards and Mellars 1996) compared to those from earlier Neolithic contexts on the west coast of Scotland, a pattern that has been reaffirmed with subsequent work (Charlton et al. 2016; Sheridan and Schulting 2020). That marine foods were used on occasion in the Neolithic is of course entirely possible, but does not substantially alter the impression of a rapid and radical shift in diet from one emphasising marine resources, to one overwhelmingly emphasising domestic terrestrial resources in terms of averaged dietary intake over a decade or more of an individual’s life (cf. Hedges et al. 2007).

Bownes et al. (2017) make a perfectly reasonable case for the use of collected near-shore marine resources, especially shellfish, to supplement a farming economy based mainly on domesticated plants and animals, and/or to act as a buffer during times of crop failure and/or herd loss. The latter, as they note, recalls the results of a study using much higher resolution sequential sampling of tooth dentine to identify periodic greater use of marine foods at West Voe on Shetland, presumably under duress rather than choice, given that these individuals seem to have experienced earlier mortality than those who do not show this pattern (Montgomery et al. 2013). But while the case may be reasonable *prima facie* and we have no argument with it as such, there are two issues with the isotopic modelling as presented in Bownes et al., one technical and the other more interpretative. We also bring new data to bear on the question of minor marine resource consumption in the form of compound-specific $\delta^{13}\text{C}$ analysis of single amino acids from Carding Mill Bay.

The model: when FRUITS go off

In their FRUITS model, Bownes et al. (2017) use $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for terrestrial faunal remains from CMB together with archaeological marine fish remains from Viking and medieval Orkney, modern fish from the North Sea, and modern shellfish from the Oban area. A considerable amount of new isotopic faunal data is used to characterise three food groups for their model, which focusses only on dietary protein: terrestrial herbivores, marine fish and marine shellfish. Herbivore and fish bone collagen values are adjusted to reflect estimated flesh protein values. Thus, for example, the mean $\delta^{13}\text{C}$ value of $-22.8 \pm 0.43\text{‰}$ derived from measurements on 13 herbivore bone collagen samples from CMB is adjusted by -1.9‰ to attain the ‘flesh’ value of $-24.7 \pm 0.1\text{‰}$ used in the model (Bownes et al. 2017: 1284, 1286) (the lower error term is due to their use of standard error rather than standard deviation, intended to better represent the averaging effect in the human consumer over many years). The archaeological fish remains are from Viking/medieval sites in Orkney and Caithness, but are probably comparable to values from the mid-Holocene of the west coast. Shellfish are more complicated, as modern flesh was measured and an additional argument made for its application to Neolithic CMB. This makes a very useful addition to the baseline isotopic data for Scotland.

Bownes et al. (2017: 1291) conclude: “First, and most significantly, the results of the FRUITS reconstruction of all four humans reveal modest amounts (15 ± 11 to $21 \pm 14\%$) of marine resources in the diet... Our results are in contrast to previous interpretations of bulk bone isotope data that suggested a complete absence of marine resources in the Neolithic diet”. Firstly, and admittedly as a relatively minor point, we take issue with the use of the word ‘reveal’: this is a modelled outcome and needs to be understood and explicitly acknowledged as such, as done elsewhere in the paper with the more appropriate term ‘suggests’. The subtle difference in word choice is important and applies to all modelling. As we demonstrate below, other outcomes are possible depending on how the model is constructed. FRUITS and other Bayesian models (e.g., MixSIAR, SIMMR (Parnell and Inger 2021; Stock et al. 2018)) can provide very useful ways of thinking about isotopic data and exploring different models in a heuristic fashion, but the output is dependent on the input and should not be taken as proven fact. Secondly, as already noted above, to allude to a ‘complete absence of marine resources’ is an exaggeration of our position, which allowed for the possibility of a minor contribution from marine foods. In another paper published in the same year we specified this as ca. 5-10% (Schulting and Richards 2002b: 1023). These matters aside, there are issues with the modelling undertaken by Bownes et al. (2017), such that their conclusion of a contribution of “up to ca. 21% of dietary protein from marine

resources” (*ibid.*: 1275) at Carding Mill Bay is unwarranted.

Fernandes et al. (2015) recommend human diet-to-collagen enrichment factors of $+4.8 \pm 0.5\text{‰}$ for $\delta^{13}\text{C}$ and $+5.5 \pm 0.5\text{‰}$ for $\delta^{15}\text{N}$. These values have been widely used in modelling (e.g., Fernández-Crespo et al. 2020; Pickard and Bonsall 2020; Sjögren 2017). If anything, it is the high $\delta^{15}\text{N}_{\text{diet-collagen}}$ enrichment factor that is more controversial. Most modelling work in ecology uses a smaller $\delta^{15}\text{N}_{\text{diet-collagen}}$ offset of ca. 3‰ (e.g., Minagawa and Wada 1984; Post 2002; Vanderklift and Ponsard 2003), but values of 3-4‰ have often been used in palaeodietary studies on humans as well (e.g., Halffmann et al. 2020; Newsome et al. 2004; Piličiauskas et al. 2017). In their own earlier work, Fernandes et al. (2012; 2014) used a comparable $\delta^{15}\text{N}_{\text{diet-collagen}}$ offset of $+3.6 \pm 1.3\text{‰}$ based on a survey of the experimental literature, mainly on rodents. This figure was subsequently changed to $+5.5 \pm 0.5\text{‰}$ based on human diet-to-hair enrichment values from the literature including an additional keratin-to-collagen offset of 1‰ (Fernandes et al. 2015: 330). The resulting figure is noted as being similar to the estimated diet-to-collagen enrichment of ca. 6‰ reported by O’Connell et al. (2012) based on $\delta^{15}\text{N}$ values of red blood cells from individuals with known diets; these authors do note, however, that a “very conservative approach to the data” would give a lower figure of ca. $+4.6\text{‰}$ (O’Connell et al. 2012: 431) that is closer to that used in the ecological literature.

By contrast, the $\delta^{13}\text{C}_{\text{diet-collagen}}$ offset follows the adage ‘you are what you eat, plus 5‰’ that has long formed the basis of stable carbon isotope analysis on collagen (Ambrose and Norr 1993; Hedges and Van Klinken 2002; Jim et al. 2006; Tieszen and Fagre 1993; van der Merwe 1989). This simplifies a more complex situation, however, as it only applies when both the protein and the energy (i.e., carbohydrate and lipid) components of the diet have similar $\delta^{13}\text{C}$ values. This will be approximately the case for cereals, which exhibit relatively little difference between protein and carbohydrate $\delta^{13}\text{C}$ values, but will differ substantially more for animal tissues where lipids are significantly depleted (by ca. 6‰) compared to protein. Nevertheless, Fernandes et al. (2012: 299) found that the figure of $+4.8 \pm 0.5\text{‰}$ still worked well for the human diets they modelled, since with animal foods the protein component dominates the collagen $\delta^{13}\text{C}$ signal due to routing (Ambrose and Norr 1993; Fernandes et al. 2012; Jim et al. 2006), and it is this value that has been used in subsequent studies employing FRUITS (Fernandes 2016; Fernandes et al. 2012; 2014; 2015; see also Andrade et al. 2015; Denaire et al. 2017; Fernández-Crespo et al. 2020; Pickard and Bonsall 2020; Sjögren 2017; Törv and Meadows 2015, etc.). To our

knowledge, the single exception to this is Bownes et al. (2017: 1287) who state: “Chosen *diet to collagen offsets* were $1 \pm 1\text{‰}$ for $\delta^{13}\text{C}$ and $5.5 \pm 0.5\text{‰}$ for $\delta^{15}\text{N}$ ” (emphasis added). No rationale is given for this departure from the widely accepted and utilised $\delta^{13}\text{C}_{\text{diet-collagen}}$ offset for humans of $4.8 \pm 0.5\text{‰}$. It was perhaps meant to stand for a trophic level offset in $\delta^{13}\text{C}$, taken to be ca. 1‰ (Bocherens and Drucker 2003), but this is wholly inappropriate as a diet-to-collagen offset. It is in this sense that Piličiauskas et al. (2017, tab. 1) apply a $\delta^{13}\text{C}$ offset of $1.0 \pm 0.2\text{‰}$ in a FRUITS model directly comparing the *bone collagen values* of prey and consumers, but this is a different approach to that taken by Bownes et al., which uses inferred herbivore and fish ‘flesh’ values in order to be able to include modern measurements on shellfish flesh in their model.

Here, we replicate the FRUITS (v3.0) models for the four directly dated human bone specimens from Carding Mill Bay with exactly the same parameters as supplied by Bownes et al. (2017: 1287) (Figure 1a; Table 1), and then re-run them with the only change being the use of a $\delta^{13}\text{C}_{\text{diet-collagen}}$ offset of $4.8 \pm 0.5\text{‰}$. Following Bownes et al., the model is a very simple one, examining only the dietary protein contribution and excluding plants from consideration. As would be expected, changing the diet-to-collagen offset from $+1 \pm 1\text{‰}$ to $+4.8 \pm 0.5\text{‰}$ makes a significant difference in the resulting modelled estimates of the protein contributions of the three sources, which is reduced to 2-3% for both marine fish and shellfish (Figure 1b; Table 2), far lower than the 15-21% estimated by Bownes et al. and perfectly in keeping with our original conclusion that marine foods made only a minimal impact on Neolithic diets at Carding Mill Bay (Schulting and Richards 2002a; indeed, it is even lower than the ‘minimal contribution’ we suggested, elsewhere defined as 5-10%). This too could be interpreted as consistent with the presence of marine fish and shellfish remains at the site (*contra* Bownes et al. 2017: 1291), accepting that this reflects a marginal aspect of the overall subsistence economy at the time, the main focus of which was no doubt elsewhere.

It might also be noted that all but one of the eight new dates on terrestrial faunal bone from the shell midden presented by Bownes et al. (2017, tab. 8) pre-date those on the humans by some two to six centuries, with all deriving from two of the same contexts – XIV and XV – that yielded two of the human bone dates (OxA-7663 and OxA-7664) (Figure 2). In fact, many of the new terrestrial faunal (and shell) dates are coeval with the latest Mesolithic presence on Oronsay. In other words, the shell midden could be interpreted as a largely Late Mesolithic context, into which Neolithic human remains were inserted centuries later. A similar finding, though with a

much greater chronological gap, was seen at Raschoille Cave, also in the Oban area. Here, Mesolithic dates obtained on faunal remains and worked bone were two to three millennia earlier than the Neolithic dates obtained on human remains found in both the lower and upper cave deposits (Bonsall 2000; Sheridan and Schulting 2020). Thus, while we agree with Bownes et al. that it is important to have baseline faunal data for the interpretation of human stable isotopic results, it is not clear in this case to what extent the faunal remains are contemporary with the human remains at CMB. Within the same cultural context a matter of a few centuries may not make much difference, but when the faunal and human dates straddle a major division in subsistence practices and landscape use, including the introduction of domesticated cereals and animals, then this becomes very relevant indeed.

In line with the findings of Montgomery et al. (2013), it may be that sequential sampling of dentine would reveal brief periods of greater marine use reflecting short-term exigencies on the west coast of Scotland during the Neolithic (and later periods). This remains for future – and would not be possible for CMB itself, as no human teeth were recovered. At present, the bulk bone collagen values for Carding Mill Bay, representing a long-term average of protein consumed over a decade or more, do not support a marine contribution of anywhere near the 15–21% claimed by Bownes et al. (2017). This also makes unnecessary their re-calibration of the human radiocarbon dates at Carding Mill Bay using mixed atmospheric/marine curves.

And while a minor marine contribution of 2–3% is entirely feasible –though statistically the most probable contribution is 0–1% (Figure 3) – it should be emphasised that, in terms of the model, even this is entirely a product of the inclusion of marine fish and shellfish. Had, for example, isotopic values for young nursing herbivores and cereals been included instead, their contribution too would be quantified and a model successfully produced with no need for any marine input whatsoever. To demonstrate this we present a new model for OxA-7890, chosen because it is modelled as showing the highest contribution of ‘marine’ protein (note that it is also the latest in the series, in fact dating to the Late Neolithic, and so furthest from any ‘continuity’ with the Mesolithic, though Bownes et al. refer to all the CMB humans as ‘Early Neolithic’). We use the same herbivore protein values of $-24.7 \pm 0.1\text{‰}$ for $\delta^{13}\text{C}$ and $3.4 \pm 0.1\text{‰}$ for $\delta^{15}\text{N}$ as provided in Bownes et al. The ‘young herbivore’ is adjusted by $+1\text{‰}$ for $\delta^{13}\text{C}$ ($-23.7 \pm 0.1\text{‰}$) and $+2\text{‰}$ for $\delta^{15}\text{N}$ ($5.4 \pm 0.1\text{‰}$), reflecting the trophic level enrichments associated with nursing animals. Estimating the appropriate isotopic values for cereals is difficult in the absence – to our

knowledge – of any direct measurements of Neolithic grains from Scotland. For the purposes of the model we use a $\delta^{13}\text{C}$ value of $-26.0 \pm 1.0\text{‰}$ for ‘cereal protein’ based on isotopic measurements of emmer wheat from Neolithic sites in England (Bogaard et al. 2013: tab. 2) and Wales (Treasure et al. 2019, tab. 7), which are themselves quite variable, especially in $\delta^{15}\text{N}$, probably reflecting both differences in natural soil ^{15}N and in manuring practices (Bogaard et al. 2013). To take this into account we ran two models, with $\delta^{15}\text{N}$ values of $5.0 \pm 2.0\text{‰}$ and $3.0 \pm 1.0\text{‰}$. Again we compare $\delta^{13}\text{C}_{\text{diet-collagen}}$ offsets of $1.0 \pm 1.0\text{‰}$ and $4.8 \pm 0.5\text{‰}$.

The results are more in keeping with what might be expected of British Neolithic farming communities, known to have practiced both cereal cultivation and animal husbandry from the outset. There is relatively little difference between the two models when varying the cereal $\delta^{15}\text{N}$ values, but there is in terms of the $\delta^{13}\text{C}_{\text{diet-collagen}}$ offsets (Table 3). For example, the contribution of cereals is modelled as ca. $20 \pm 18\%$ using the 1.0 ± 1.0 offset, but as ca. $48 \pm 22\%$ using the 4.8 ± 0.5 offset. While the contribution of herbivores is similar in all four models at ca. 30-35%, that of young nursing herbivores reduces from $47 \pm 23\%$ using the 1.0 ± 1.0 offset to $22 \pm 15\%$ using the $4.8 \pm 0.5\text{‰}$ offset. Again, we see this as a heuristic exercise and make no claim to have ‘revealed’ the actual proportion of these three food groups consumed by the Neolithic communities around Carding Mill Bay. For one thing, a concentration dependent model would be required to reflect the energy (lipid and carbohydrate) fraction of the diet (Ambrose and Norr 1993; Fernandes et al. 2012; Jim et al. 2006). The point of the exercise in this case is simply to demonstrate the flexibility of Bayesian models such as FRUITS. This is both a strength and, when used uncritically, a weakness (cf. Cheung and Szpak 2020). When marine fish and shellfish are entered into the model, i.e., they are assumed *a priori* to make a dietary contribution, and so will be modelled as such.

An alternative model excluding marine foods entirely is perfectly capable of resolution, as demonstrated above. We might also include freshwater fish as a dietary source, and again they would be modelled as making some minor contribution. Yet another entirely plausible model might include terrestrial herbivores that seasonally graze on or were foddered with seaweed, such as has been demonstrated isotopically for a number of Neolithic and Bronze Age sheep on Orkney (Balasse et al. 2005; 2009; Schulting et al. 2017; see also Jones et al. 2013). This, alongside marine resources consumed directly, was suggested to be a possible contributor to the elevated $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values (the highest adult having values of -19.1‰ and 11.0‰ ,

respectively, i.e., higher on both accounts than any of the Carding Mill Bay humans) found in some individuals at the Early Neolithic site of Holm of Papa Westray North on Orkney (Schulting and Richards 2009). Whether or not seaweed foddering occurred on the west coast of Scotland during the Neolithic is unknown at present, but it provides a plausible alternative source of ‘marine’ protein. The signal is not detectable in adult animals without sequential sampling of teeth (Balasse et al. 2019), and so would be easily lost in the adult herbivore bone collagen from Carding Mill Bay measured by Bownes et al. (2017); nor, in the absence of species identifications, is it clear that these even belong to domestic herbivores in any case – given their early radiocarbon dates, many are likely to be wild fauna and may be better understood within a Mesolithic context as discussed above. By the same reasoning, the claim by Bownes et al. (2017: 1292) that their herbivore data from CMB demonstrate the absence of manuring and foddering practices for domestic animals in the Neolithic cannot be sustained without species identifications confirming their domestic status (e.g., using ZooMS).

Thus, it is important to consider a model’s outputs in this light. They are ‘what if’ scenarios, much in the same way as Bayesian modelling of radiocarbon dates allows their exploration under different assumptions (Bayliss and Whittle 2007; Bronk Ramsey 2009; Buck et al. 1996). In fact, there are far fewer assumptions in the modelling of radiocarbon dates than of stable isotopic data, given uncertainties over both the number of diet sources and their isotopic values, and the various offsets required to translate diet values into – in this case – bone collagen values.

Another issue with Bownes et al.’s (2017) interpretation of the palaeodietary modelling at Carding Mill Bay is that it takes no account of the wider body of isotopic data available for the British and Irish Neolithic². While some interesting regional patterning is emerging (Schulting and Boric 2017; Schulting et al. forthcoming), it has been repeatedly demonstrated (Richards et al. 2003; Schulting 2013; Schulting and Boric 2017) that – Sumburgh, Shetland aside – there is essentially no isotopic difference between individuals found on coastal/near-coastal (within 10 km) and inland sites across Britain and Ireland, with mean $\delta^{13}\text{C}$ values of $-20.8 \pm 0.6\text{‰}$ ($n = 231$) for the former and $-21.0 \pm 0.5\text{‰}$ ($n = 198$) for the latter. Corresponding mean $\delta^{15}\text{N}$ values

² There is a larger dataset than that for the directly dated individuals at CMB. In total 10 samples were run, with mean results of $-21.4 \pm 0.2\text{‰}$ and $9.3 \pm 0.4\text{‰}$ for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, respectively. Nor do these results differ significantly from three samples from the nearby chambered tomb at Crarae, with corresponding values of $-21.6 \pm 0.3\text{‰}$ (heteroscedastic Student’s t -test, $t = 1.697$, $df = 2$, $p = 0.232$) and $9.2 \pm 0.3\text{‰}$ (heteroscedastic Student’s t -test, $t = 0.767$, $df = 6$, $p = 0.472$).

are $9.8 \pm 1.0\text{‰}$ ($n = 185$) for coastal sites and 9.6 ± 0.6 ($n = 190$) for inland sites (Schulting and Boric 2017, tab. 7.3). Nor is there even a weak correlation between $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values as would be expected with a marine contribution of up to ca. 20% (cf. Richards and Hedges 1999). While detecting small contributions of marine (or any other) foods using bulk bone collagen at the level of the *individual* is very difficult, at the *population* level this should be observable in the form of small but statistically significant differences between coastal and inland groups. That this is demonstrably not the case in Neolithic Britain and Ireland despite a large sample size must form part of the context for the interpretation of those challenging individual results. Given that the mean $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values from inland sites are very similar to those from Carding Mill Bay, the implication of Bownes et al.'s results is that similar contributions of marine fish and shellfish could be found by Bayesian modelling for all British and Irish Neolithic sites, regardless of their distance to the coast.

To demonstrate this, we model one individual from Whitwell long cairn, Derbyshire, located ca. 100 km from the nearest coast. The individual has been directly dated to 4872 ± 32 BP (OxA-14485: 3709-3542 cal BC – approximately contemporary with two of the dated individuals at Carding Mill Bay), with $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of -20.2‰ and 9.8‰ , respectively (Vyner 2011). These values are typical for the site. Using the same parameters as employed by Bownes et al. (2017) for Carding Mill Bay (i.e., with a $\delta^{13}\text{C}_{\text{diet-collagen}}$ enrichment factor of $1 \pm 1\text{‰}$), OxA-14495 is modelled as having ca. 20% dietary marine protein (Table 4), similar to the Scottish site. Changing the $\delta^{13}\text{C}_{\text{diet-collagen}}$ enrichment factor to the correct value of $4.8 \pm 0.5\text{‰}$ reduces the total 'marine' contribution to ca. 7%. To say the least, both estimates are highly improbable on archaeological grounds (there is no evidence for contact with the coast for subsistence purposes at Whitwell or neighbouring sites). Again, the exercise serves to make the point that if a food group is entered, it will invariably be modelled as potentially making some contribution to the diet. Moreover, as discussed above, while some minor use of marine resources may be entirely feasible for the Neolithic, it is not clear that the fish and shellfish remains at Carding Mill Bay are of the same age as the humans, calling into question the necessity of including them in the model at all; again, we do not dispute the heuristic value of this, but the interpretation of the model results requires greater nuance, including consideration of the wider context.

Compound-specific $\delta^{13}\text{C}$ analysis of single amino acids

Finally, to further understand the diets of the CMB humans we undertook compound-specific isotope analysis (CSIA) of collagen amino acids from humans and fauna. This analysis can provide a higher level of detail about past diets than bulk collagen values, allowing comparisons of the isotope values of essential and non-essential amino acids. This method has been used to identify whether humans were consuming significant amounts of freshwater (Honch et al. 2012) or marine foods (Choy et al. 2010; Halffman et al. 2020; Honch et al. 2012; Raghavan et al. 2010; Webb et al. 2018), as well as and the relative importance of C₃ and C₄ plants in diets (Choy et al. 2010; Honch et al. 2012; Ma et al. 2021). In this study we measured the stable carbon isotope ratio ($\delta^{13}\text{C}$) of 13 amino acids from four humans, one red deer and one pig from the site (Table 5). Bulk isotopic measurements were also made, and are very similar to those previously published (compare values in Table 2 and in Schulting and Richards 2002a: table 2).

Collagen samples previously prepared for bulk isotope measurements were derivatized for CSIA analysis on a GC-C-IRMS at the Archaeology Isotope Laboratory at the Department of Archaeology, Simon Fraser University, Canada. Samples were derivatized to *N*-acetyl isopropyl (NAIP) esters following methods outlined in Kubiak et al. (2021). Derivatized amino acids were measured compared to an internal standard (known value) amino acid mix (Kubiak et al. 2021) and two internal standards. Measurements were undertaken using a Thermo GC-C coupled to a Thermo Delta V isotope ratio mass spectrometer.

Honch et al. (2012) provided important baseline data on human amino acid $\delta^{13}\text{C}$ CSIA values which dataset identified humans with a diverse range of diets and provide the $\delta^{13}\text{C}$ values of collagen amino acids for each dietary group. This reference dataset, and other datasets subsequently contributed by other researchers (e.g. Choy et al. 2010; Webb et al. 2015; Webb et al. 2018), have been used to categorize dietary groups (e.g. Ma et al. 2021; Halffman et al. 2020). Rather than comparing all of the $\delta^{13}\text{C}$ data from all of the amino acids (although this is also possible using the mixing model developed by Larsen et al. 2013) most researchers focus on differences in values between key amino acids as a way to discriminate between diets from the different subsistence regimes. For example, Webb et al. (2015; 2018) and Ma et al. (2021) compare the difference between the measured values of the essential amino acid lysine ($\delta^{13}\text{C}_{\text{lys}}$) with the difference in $\delta^{13}\text{C}$ values between both glycine and phenylalanine ($\Delta^{13}\text{C}_{\text{gly-phe}}$) and valine and phenylalanine ($\Delta^{13}\text{C}_{\text{val-phe}}$) of the reference values. A recent paper by Halffman *et al.* (2020) restricts the comparison to only essential amino acids, specifically comparing the differences between valine-phenylalanine and lysine-phenylalanine to those same values from previously

published studies. Halffman et al. conclude that the CSIA data in their study show a measurable amount of marine food contribution to the diets of two humans from Alaska that is not as apparent from bulk collagen isotope values.

Here we employ the approach taken by Halffman et al. (2020) and have plotted the $\Delta^{13}\text{C}_{\text{val-phe}}$ against the $\Delta^{13}\text{C}_{\text{lys-phe}}$ of the CMB humans and fauna compared to data from a range of previous studies (see Appendix 1). The focus on essential amino acids is in keeping with Bownes et al.'s (2017) modelling of only the protein component of the diet. In the absence of comparative single amino acid data from Neolithic Scotland for marine and terrestrial (C_3) diets we use previously published data from the UK, Europe, Japan and Korea (cf. Halffman et al. 2020). The CMB humans and animals plot clearly within the range of C_3 consumers (humans and fauna) observed by other researchers (Figure 4). There is no evidence from the CSIA data of any significant marine food contribution to diets, and certainly no evidence that marine foods were formed up to 20% of the diet.

Conclusions

Critically revisiting previous conclusions and the data on which they were based is an important part of scientific research. Bownes et al.'s (2017) paper makes a valuable contribution to research on Carding Mill Bay and the Scottish Neolithic by presenting new stable isotopic data for terrestrial and marine fauna from the site. Their comparison of ancient and modern fauna offers a useful approach to determining when modern stable isotopic data are relevant and when they are not (as with the terrestrial fauna, which showed a significant difference between the two periods, even when corrected for the fossil fuel effect). This is particularly important in allowing a case to be made for the use of isotopic measurements on modern shellfish flesh as a proxy for ancient values. They also provide a series of new radiocarbon dates on fauna from the site, using it to refine the marine reservoir effect on the west coast of Scotland during the mid-Holocene. What they do not do, however, is revise our previous conclusions regarding the minimal stable isotopic evidence for marine protein in the diets of Neolithic humans at Carding Mill Bay. An error in the $\delta^{13}\text{C}_{\text{diet-collagen}}$ offset used in their Bayesian model overestimates the contribution of marine fish and shellfish to human diets at the site by nearly an order of magnitude. Even aside from this, by omitting any consideration of the wider British Neolithic context, they miss the opportunity to critically assess the implications of their claims, which would result in models producing comparable but wholly unrealistic estimates of marine resource consumption in both

coastal and inland contexts throughout Britain and Ireland, and indeed throughout continental Europe. The lack of any significant consumption of marine resources is confirmed by CSIA of $\delta^{13}\text{C}$.

Bayesian modelling of stable isotope data using FRUITS and other platforms offers a valuable tool with which to explore various possible diet scenarios. But the output needs to be understood in that light. It cannot be taken uncritically at face value to have demonstrated past human diets. When modelling radiocarbon dates, multiple models are often used to explore the data, with an argument then made for a ‘preferred model’, based on both how well the model performs (e.g., how well it accommodates a sequences of dates) but also on the wider archaeological context. We suggest that Bayesian modelling of palaeodiets should be approached in the same way.

Author contributions

Rick Schulting: conceptualization; formal analysis; visualization; writing – original draft preparation. Rebecca MacDonald: investigation. Michael Richards: writing – original draft preparation; funding acquisition.

Data availability

All data are presented in the paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures and Tables

Figure 1a) FRUITS boxplot for CMB OxA-7890 modelled following Bownes et al. (2017);
b) re-modelled using $\delta^{13}\text{C}_{\text{diet-collagen}}$ offset of $4.8 \pm 0.5\text{‰}$.

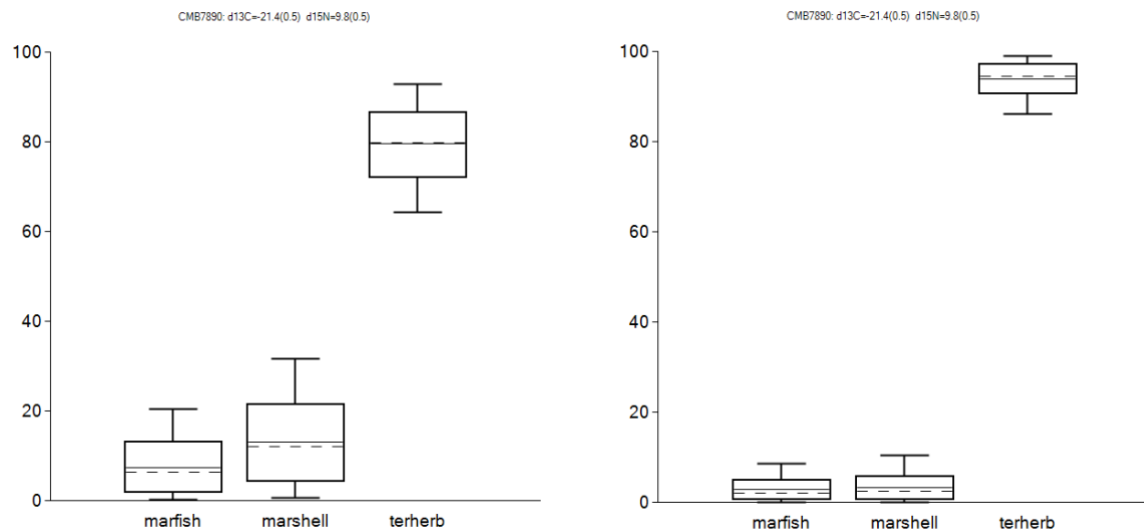


Figure 2. Plot of faunal dates (from Bownes et al. 2017) and human dates (from Schulting and Richards 2002a) from Carding Mill Bay, recalibrated using IntCal20 (Reimer et al. 2020) in OxCal v4.4 (Bronk Ramsey 2021).

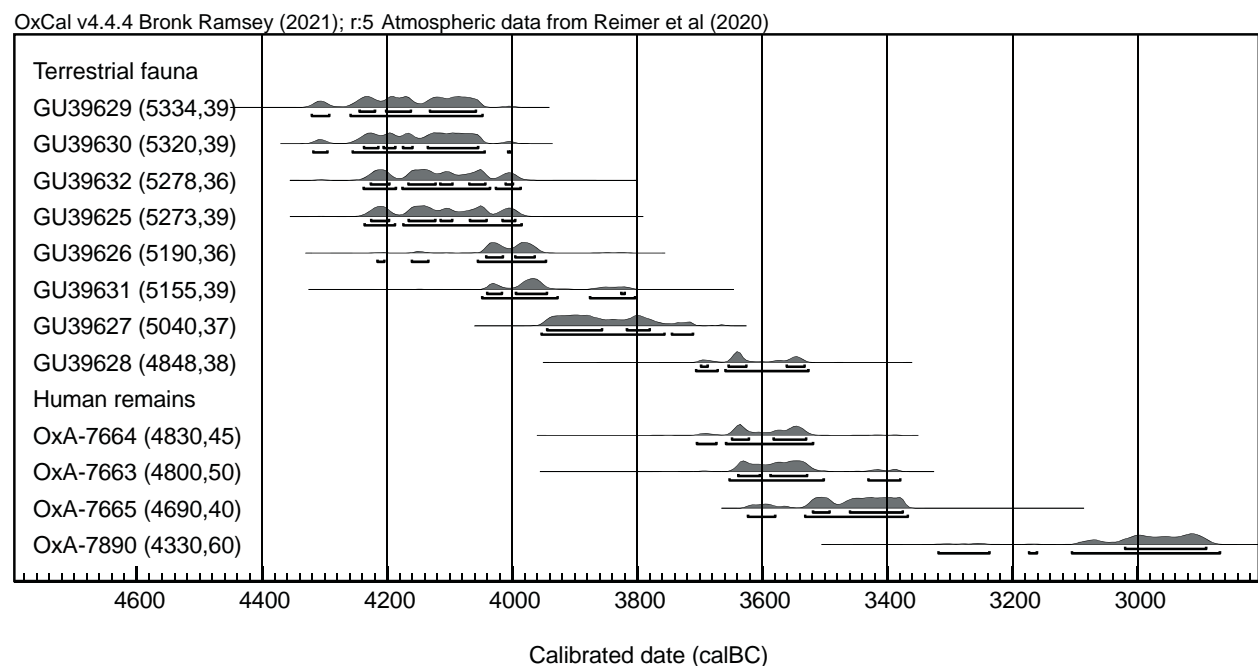


Figure 3. FRUITS histogram for CMB OxA-7890 as modelled in Figure 1b.

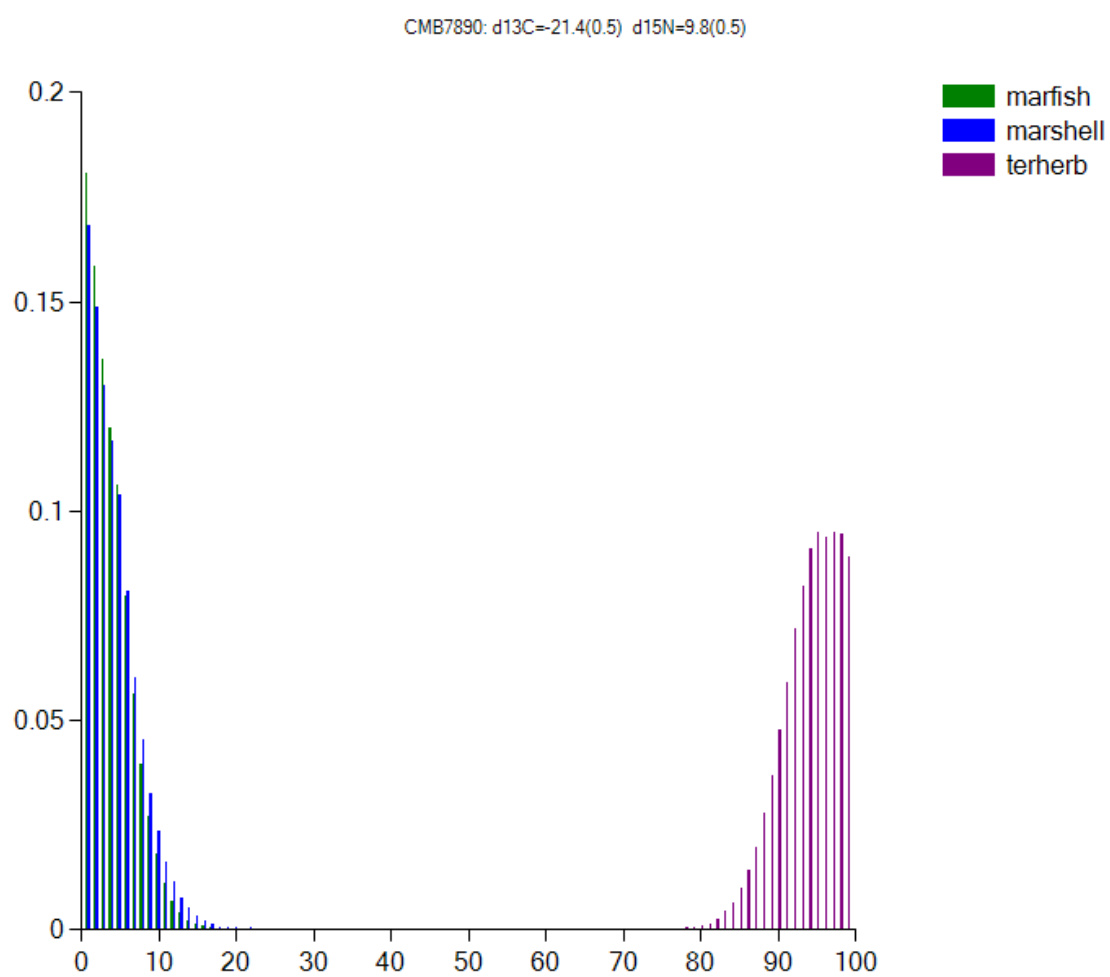


Figure 4. Plot of the differences in $\delta^{13}\text{C}$ values of the amino acids valine-phenylalanine and lysine-phenylalanine of collagen of marine, freshwater, and C_3 -terrestrial consumers. Marine human and faunal data are from (Choy et al. 2010; Honch et al. 2012; Webb et al. 2018, Raghavan et al. 2010), freshwater human (FW) data are from (Honch et al. 2012), and C_3 human and faunal data are from (Choy et al. 2010; Honch et al. 2012; Webb et al. 2015; Webb et al. 2018; this study).

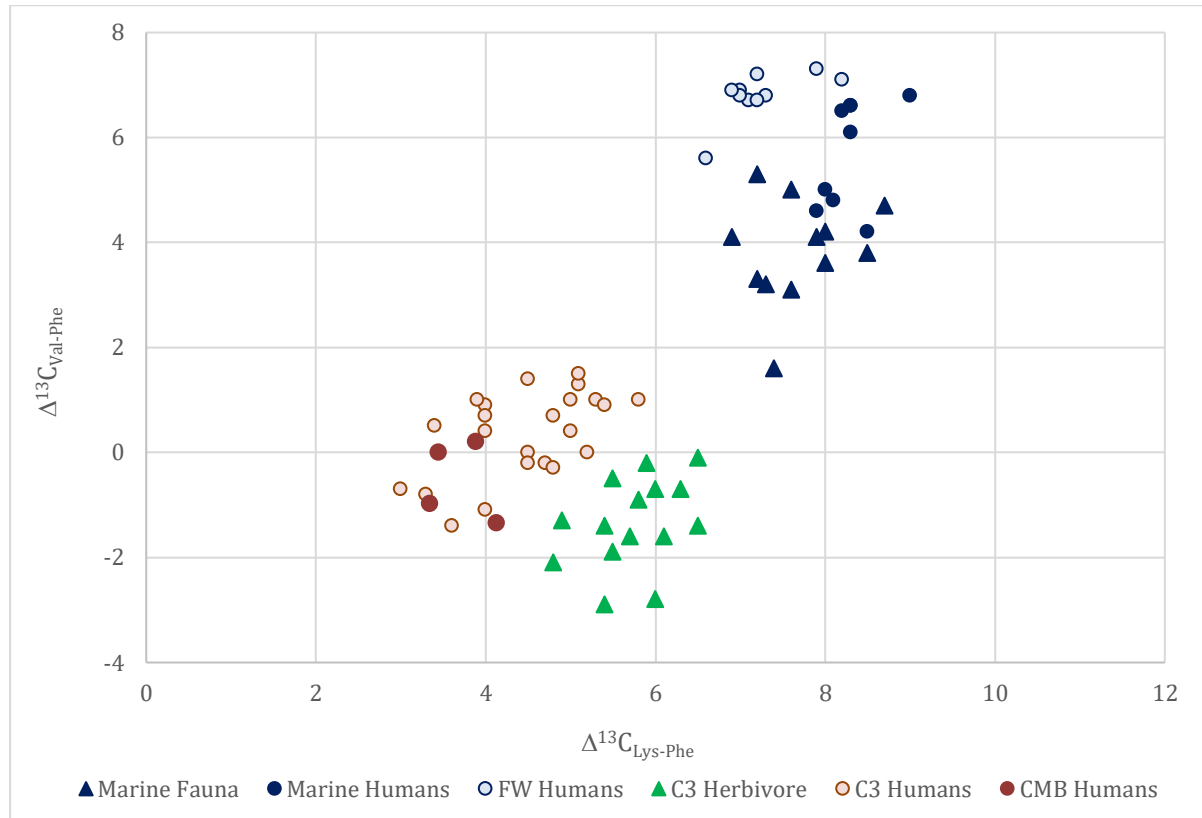


Table 1. Source diet $\delta^{13}\text{N}$ and $\delta^{15}\text{N}$ values from Bownes et al. (2017: 1287)

<i>Diet source</i>	$\delta^{13}\text{C}$	\pm	$\delta^{15}\text{N}$	\pm
Herbivores	-24.7	0.1	3.4	0.1
Marine fish	-16.8	0.1	12.9	0.3
Marine shellfish	-15.2	0.1	9.5	0.2

Table 2. Estimated protein contributions from FRUITS for Carding Mill Bay, using marine fish, marine shellfish and terrestrial nursing herbivores as the three food sources (protein only). The minor differences in model 1 are due to small stochastic differences between model runs accentuated by rounding.

<i>Source</i>	<i>Contribution % \pm 1SD</i>		
	<i>Bownes et al.¹</i>	<i>this paper¹</i>	<i>this paper²</i>
Carding Mill Bay XXIII, OxA-7890 (4330 \pm 60 BP, -21.4, 9.8)			
marine fish	8 \pm 6	7 \pm 6	3 \pm 2
marine shellfish	13 \pm 8	13 \pm 8	3 \pm 3
terrestrial herbivore	79 \pm 7	80 \pm 7	94 \pm 3
Carding Mill Bay VII:130, OxA-7665 (4690 \pm 40 BP, -21.5, 9.6)			
marine fish	7 \pm 5	7 \pm 5	3 \pm 3
marine shellfish	12 \pm 8	12 \pm 8	2 \pm 2
terrestrial herbivore	81 \pm 7	81 \pm 7	95 \pm 3
Carding Mill Bay XV:1, OxA-7664 (4830 \pm 45 BP, -21.0, 8.9)			
marine fish	6 \pm 5	6 \pm 5	3 \pm 2
marine shellfish	10 \pm 7	11 \pm 7	3 \pm 2
terrestrial herbivore	84 \pm 6	84 \pm 7	95 \pm 3
Carding Mill Bay XIV:1, OxA-7663 (4800 \pm 50 BP, -21.5, 9.0)			
marine fish	5 \pm 4	5 \pm 4	2 \pm 2
marine shellfish	10 \pm 7	10 \pm 7	2 \pm 2
terrestrial herbivore	85 \pm 6	85 \pm 7	95 \pm 3

Using the model parameters supplied in Bownes et al. 2017, with:

- 1) $\delta^{13}\text{C}_{\text{diet-collagen}}$ offset of $1.0 \pm 1.0\text{‰}$
- 2) $\delta^{13}\text{C}_{\text{diet-collagen}}$ offset of $4.8 \pm 0.5\text{‰}$

Table 3. Estimated dietary contributions from FRUITS for Carding Mill Bay OxA-7890, using adult and nursing herbivores and cereals as the three food sources (protein only).

<i>Source</i>	<i>Contribution % \pm 1SD</i>	
	<i>this paper¹</i>	<i>this paper²</i>
Carding Mill Bay XXIII, OxA-7890 (-21.4, 9.8)		
terrestrial herbivore	35 \pm 22	33 \pm 22
young herbivore	45 \pm 23	20 \pm 15
cereals ($\delta^{15}\text{N}$ 5 \pm 2‰)	20 \pm 18	47 \pm 22
Carding Mill Bay XXIII, OxA-7890 (-21.4, 9.8)		
terrestrial herbivore	31 \pm 22	29 \pm 21
young herbivore	48 \pm 23	24 \pm 16
cereals ($\delta^{15}\text{N}$ 3 \pm 1‰)	21 \pm 18	48 \pm 21

1) $\delta^{13}\text{C}_{\text{diet-collagen}}$ offset of 1.0 \pm 1.0‰

2) $\delta^{13}\text{C}_{\text{diet-collagen}}$ offset of 4.8 \pm 0.5‰

Table 4. Estimated protein contributions from FRUITS for Whitwell, using – for heuristic purposes only – marine fish, marine shellfish and terrestrial nursing herbivores as the three food sources (protein only) (data from Vyner 2011).

<i>Source</i>	<i>Contribution % \pm 1SD</i>	
	<i>1.0‰ offset¹</i>	<i>4.8‰ offset²</i>
Whitwell, OxA-14495 (4872 \pm 32 BP, -20.2, 9.8)		
marine fish	7 \pm 5	4 \pm 3
marine shellfish	12 \pm 8	3 \pm 3
terrestrial herbivore	81 \pm 7	93 \pm 4

1) $\delta^{13}\text{C}_{\text{diet-collagen}}$ offset of 1.0 \pm 1.0‰

2) $\delta^{13}\text{C}_{\text{diet-collagen}}$ offset of 4.8 \pm 0.5‰

Table 5: $\delta^{13}\text{C}$ values of individual amino acids from CMB humans and fauna. Starred (*) samples have been previously directly radiocarbon dated (Schulting and Richards 2002a). Figure 1a) FRUITS boxplot for CMB OxA-7890 modelled following Bownes et al. (2017); b) re-modelled using $\delta^{13}\text{C}_{\text{diet-collagen}}$ offset of $4.8 \pm 0.5\text{‰}$.

<i>Sample ID</i>	<i>Species</i>	$\delta^{13}\text{C}_{\text{bulk}}$	$\delta^{15}\text{N}_{\text{bulk}}$	<i>ala</i>	<i>val</i>	<i>gly</i>	<i>leu</i>	<i>nor</i>	<i>pro</i>	<i>thr</i>	<i>asp</i>	<i>ser</i>	<i>glu</i>	<i>phe</i>	<i>hyp</i>	<i>lys</i>
IV:94	human	-21.5	10.1	-28.7	-27.3	-18.9	-30.4	-30.4	-21.6	-18.4	-21.5	-16.4	-25.2	-27.3	-21.0	-23.9
XXIII*	human	-21.5	9.6	-28.4	-26.9	-18.8	-30.6	-30.6	-21.4	-17.7	-23.6	-15.6	-24.9	-27.1	-21.0	-23.2
VII:112	human	-21.6	9.0	-27.7	-26.8	-18.1	-30.3	-30.2	-21.0	-17.4	-22.4	-14.3	-24.7	-25.8	-19.6	-22.4
XIV:1*	human	-21.5	9.5	-27.7	-26.7	-18.6	-31.0	-30.0	-20.8	-16.5	-22.1	-12.8	-24.4	-25.4	-19.4	-21.2
XVII:4	red deer	-23.5	3.7	-27.5	-30.0	-20.4	-33.6	-30.0	-22.0	-19.9	-21.1	-16.4	-23.9	-25.7	-20.7	-20.5
XXIV:2	pig	-22.9	4.1	-25.7	-28.6	-19.0	-31.2	-30.1	-21.1	-16.5	-22.7	-15.2	-24.3	-25.6	-19.2	-22.1